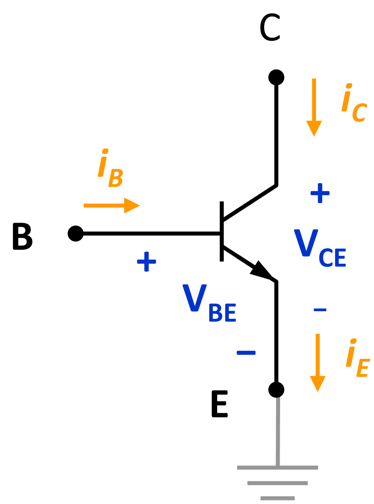
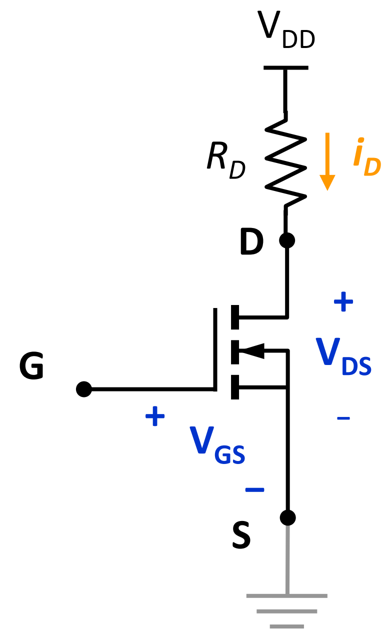
FROM LAST TIME…

Electronic Systems

- Active components (transistors) as switches





UNIT 2:
ELECTRONIC SYSTEMS

PART D: ANALOG INTERFACING

TRANSISTORS ALLOW "LOW POWER" TO CONTROL "HIGH POWER"

"High Power" (> 500 mW)	"Low Power" (< 50 mW)
▪ >100 mA, >5V ▪ Actuators • DC motors • Stepper motors • Solenoids ▪ Some sensors • IR sensors ▪ Big LEDs	▪ ~10 mA, 3.3 or 5 V ▪ Microcontrollers • Controlling motors • Reading sensors • Processing controllers ▪ Some sensors ▪ Small LEDs

MECHATRONIC SYSTEMS REQUIRE POWER AMPLIFICATION

- Many electro-mechanical loads have a low resistance, requiring an emphasis on current gain
- Unlike power amps for communication and audio systems, a DC response is often necessary.
- For most mechanical systems, power stage bandwidth (−3 dB) is rarely above 10 kHz.

OPTIONS FOR ACHIEVING AMPLIFICATION?

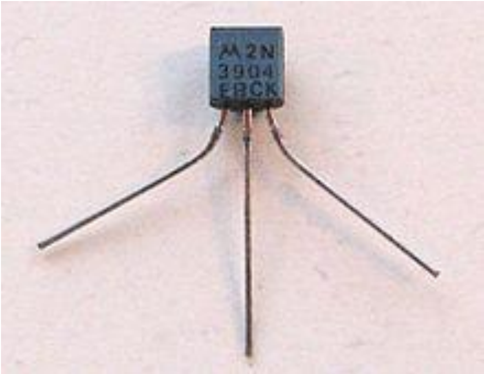
When driving a motor, should we operate a transistor in linear amplification mode or saturation mode?

- Linear amplification controls speed with the base current or gate voltage
- Saturation controls speed with duration of on/off periods
  - Similar to modulation
  - Motor acts as a low-pass filter

Define efficiency in terms of power: $\eta = \frac{P_{out}}{P_{in}}$

HOW MUCH POWER DO YOU NEED?

Low Power NPN (2N3904)



i_C (max): 200 mA

P_D: 625 mW

β: 100-300

High-Power NPN (2N3055)

i_C (max): 15 A

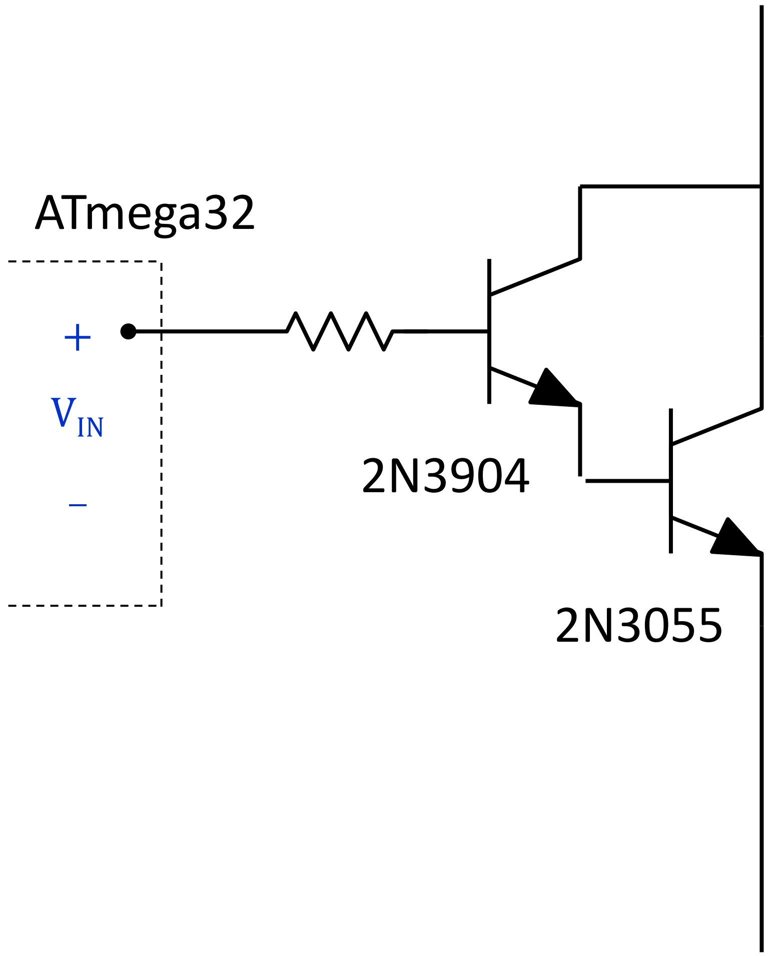
P_D: 115 W

β : 20-70

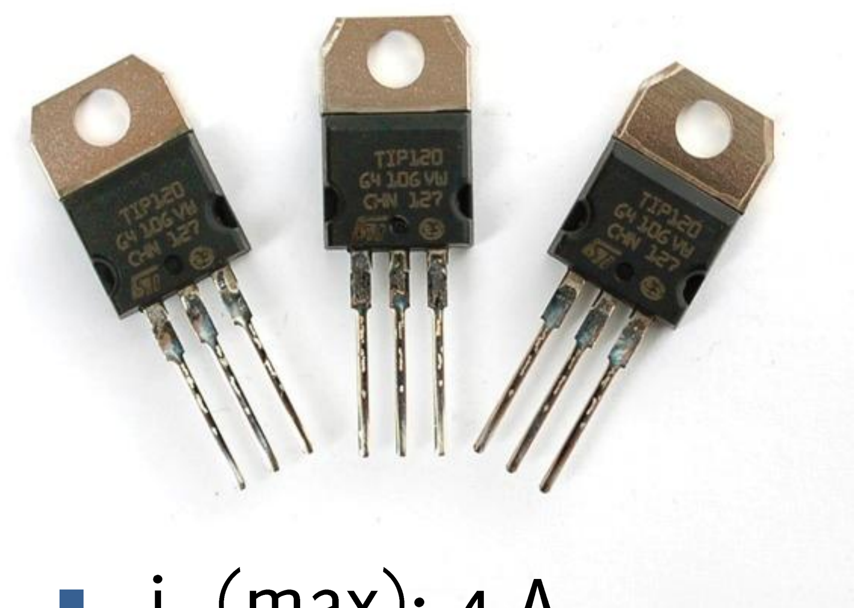
Images: https://upload.wikimedia.org/wikipedia/commons/thumb/4/4c/2N3904.jpg/220px-2N3904.jpg
https://en.wikipedia.org/wiki/File:Toshiba_2n3055_transistor.jpg

Will likely need a heat sink!

A DARLINGTON PAIR CAN PROVIDE HIGH AMPLIFICATION



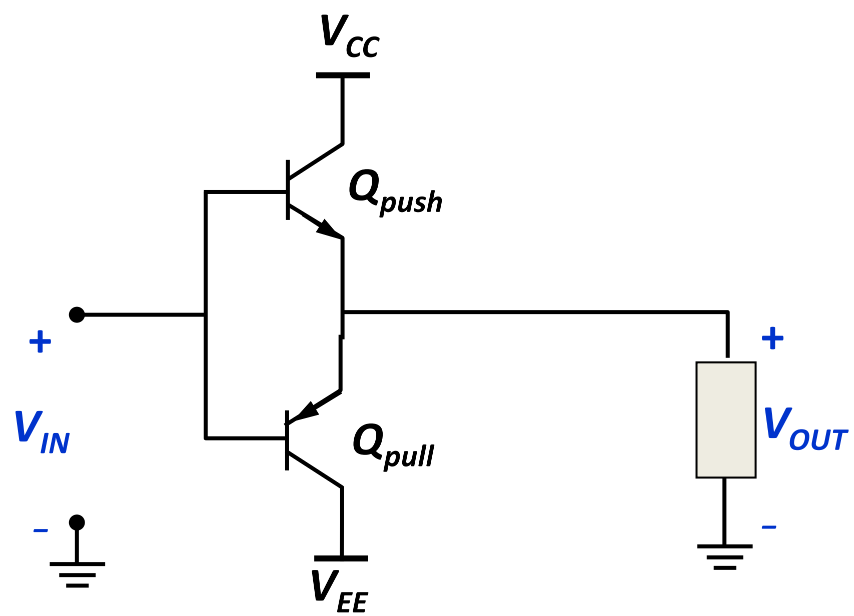
Medium Power Darlington Pair (TIP120)



- i_c (max): 4 A
- P_D: 65 W
- β: 2500

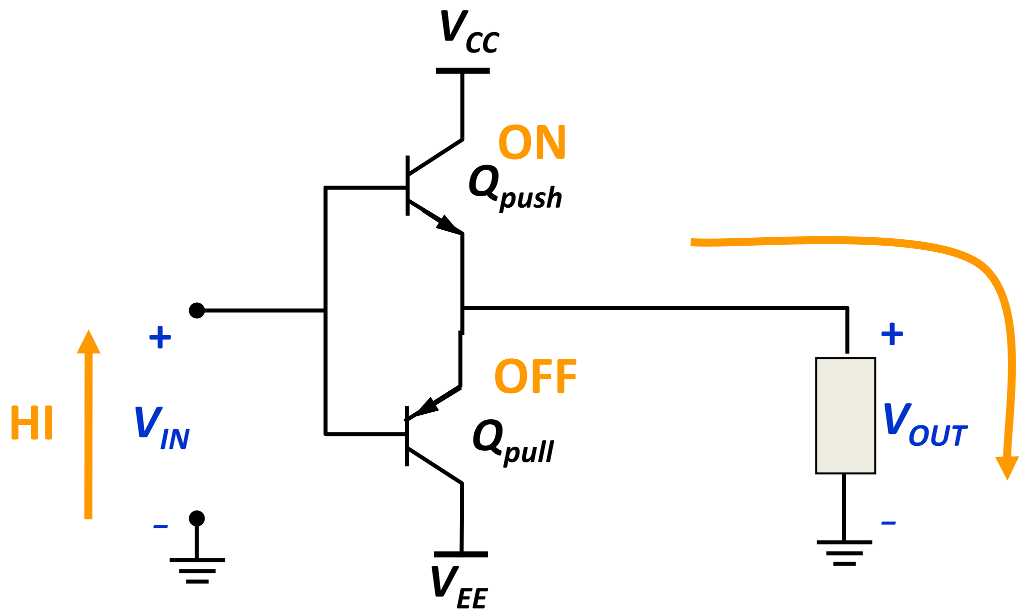
Image: https://www.adafruit.com/index.php?main_page=popup_image&pID=976

AMPLIFIERS CAN PROVIDE DIRECTIONAL CONTROL



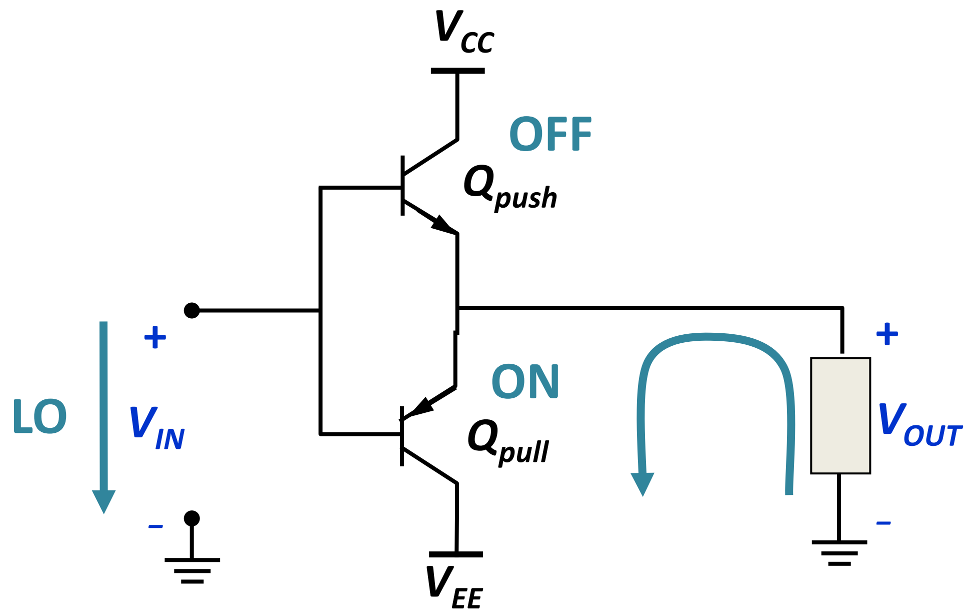
- Push-Pull (class B) power (output) stage

AMPLIFIERS CAN PROVIDE DIRECTIONAL CONTROL



- Push-Pull (class B) power (output) stage

AMPLIFIERS CAN PROVIDE DIRECTIONAL CONTROL



- Push-Pull (class B) power (output) stage

AMPLIFIERS

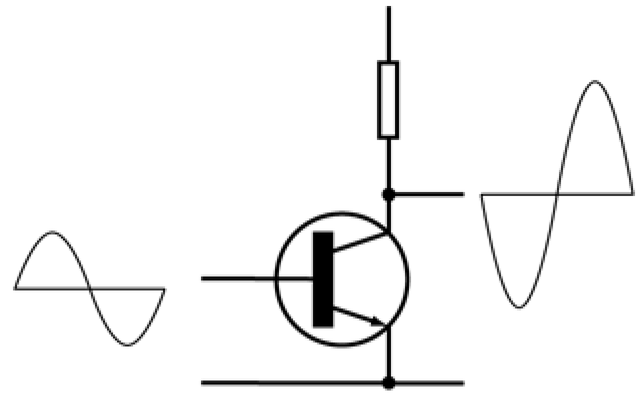


Image: https://en.wikipedia.org/wiki/File:Electronic_Amplifier_Class_A.png

"Class A"

- Transistor in linear amplification region at all times
- Requires only a single transistor; simple to build
- *Maximum* efficiency of 25%

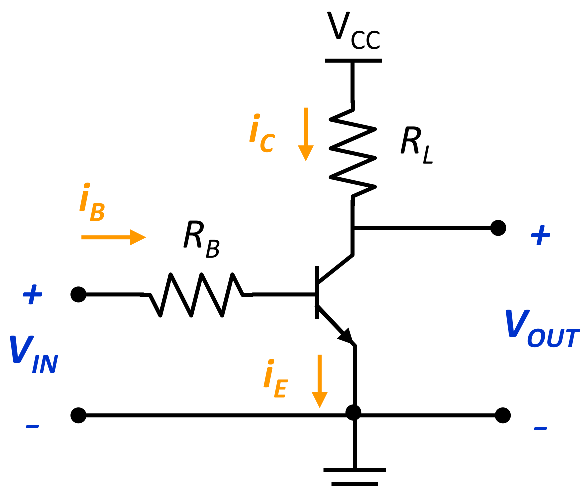
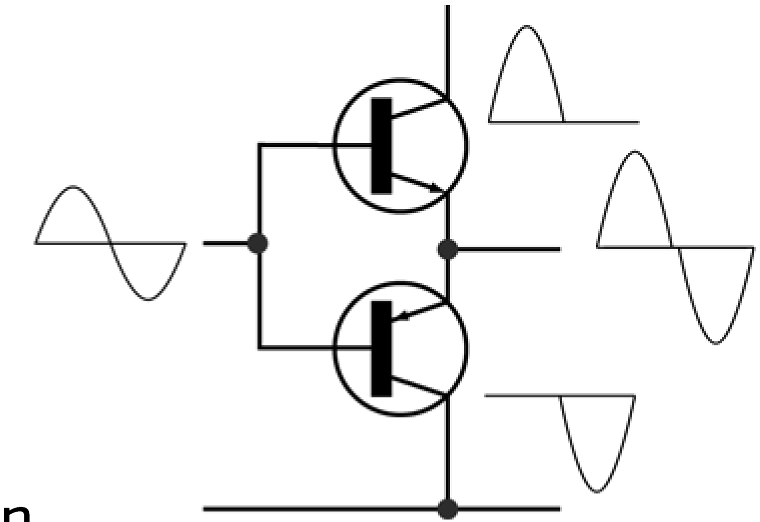


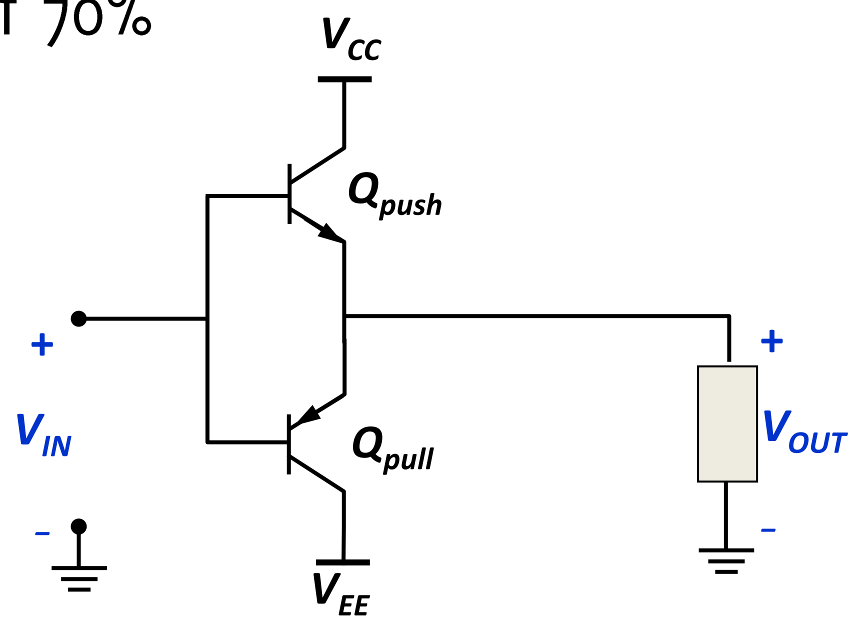
Image: https://en.wikipedia.org/wiki/File:Electronic_Amplifier_Push-pull.svg

AMPLIFIERS



"Class B"

- Push-pull amplifier
- Subject to "crossover distortion
- Maximum efficiency of 78%
- Typical efficiency of 70%



AMPLIFIERS

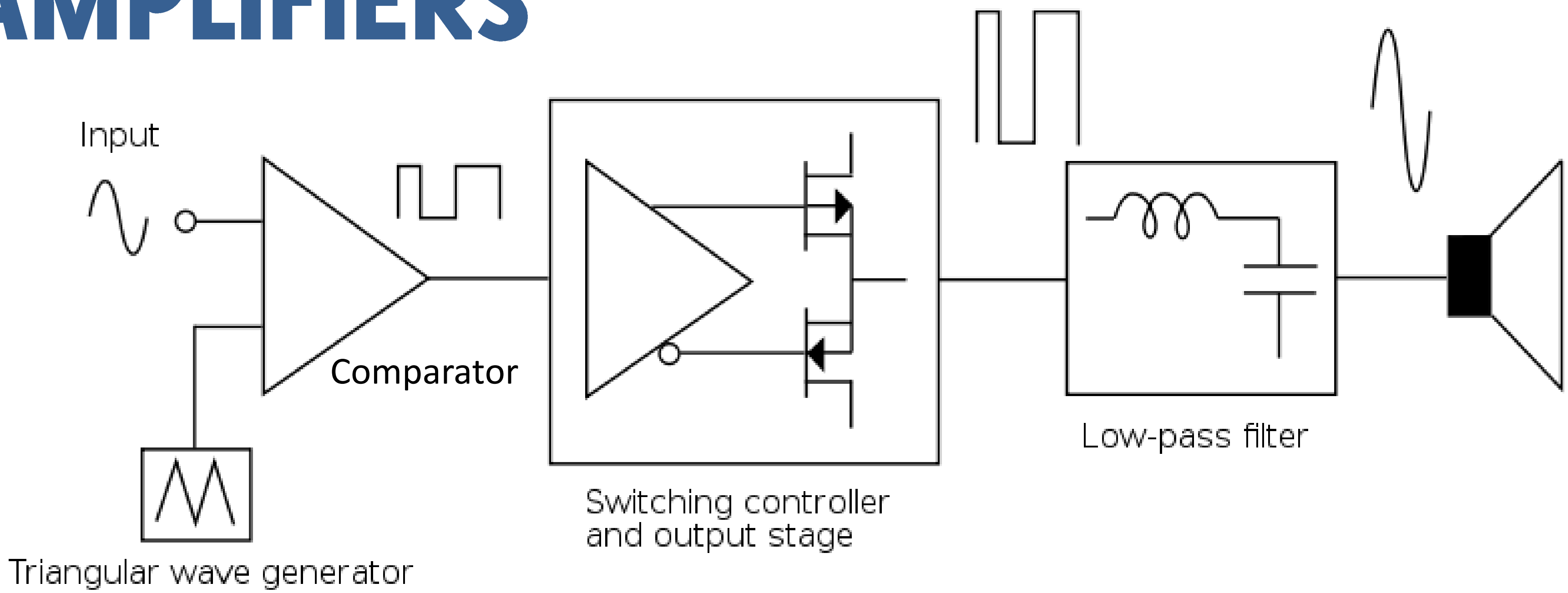
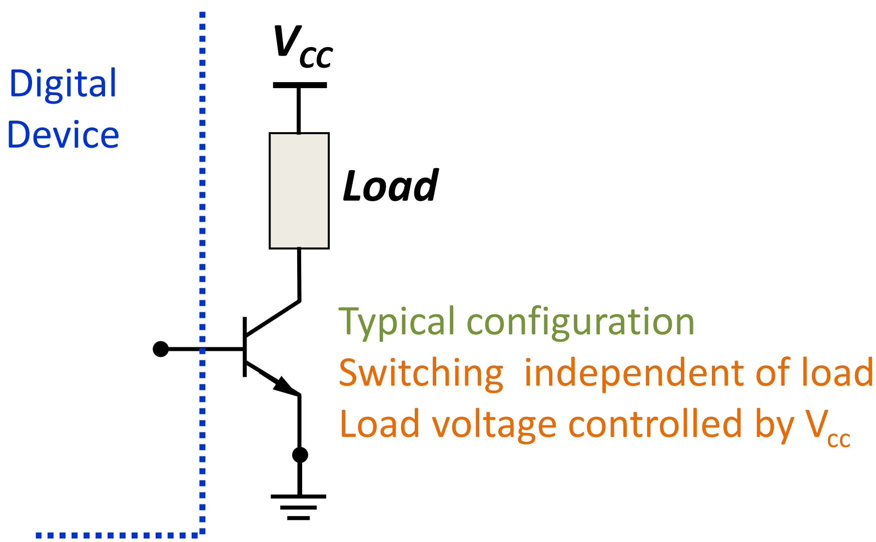


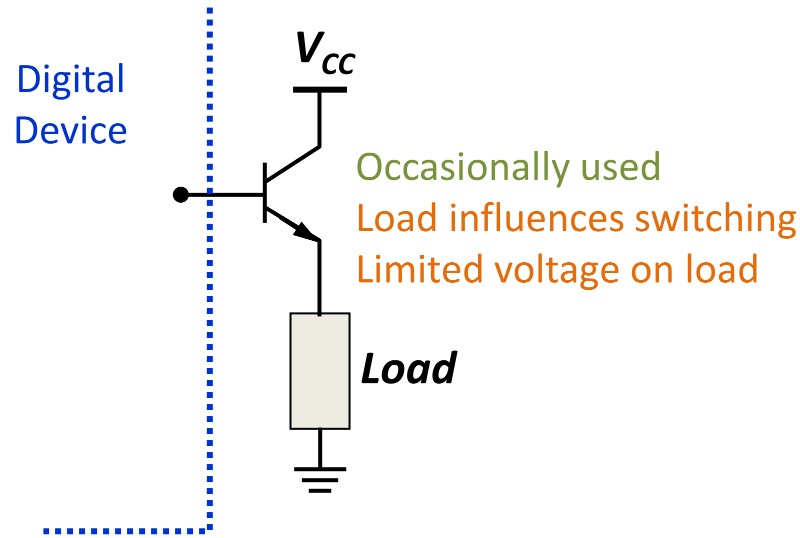
Image: https://en.wikipedia.org/wiki/File:Pwm_amp.svg

"Class D" amplifier

- Transistors act in saturation mode (switching on and off)
- Motor acts as low-pass filter
- Maximum theoretical efficiency of 100%
- Typical efficiency of 80% to 95%

WHERE TO PLACE THE LOAD?

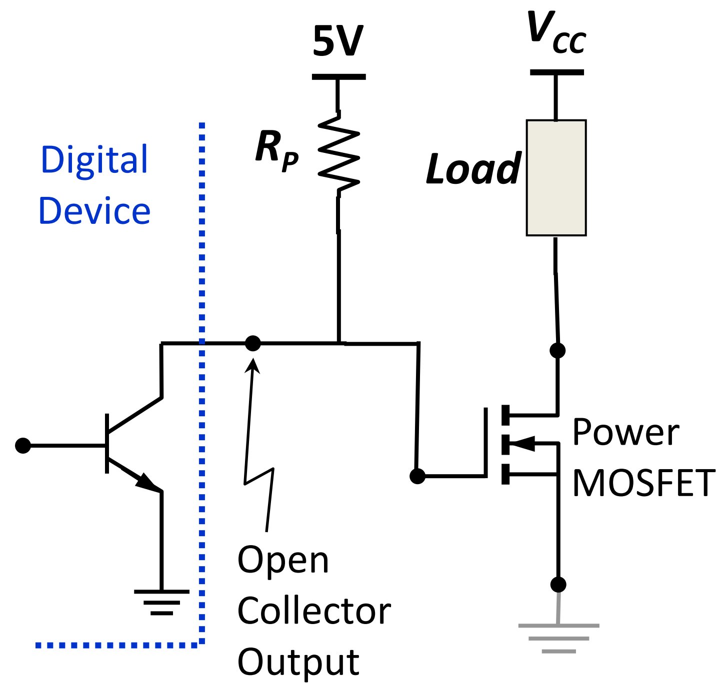




- Turn-on/off currents to actuators and sensors – controlling the current flow (turning on/off a device)
- Can be connected directly to a digital output (if the digital output stage can supply the required base current)

DIGITAL DEVICE OUTPUTS MAY BE OPEN-COLLECTOR OF A BJT

- Base-emitter junction of BJT transistor turned on/off with digital output
- Need to connect the output (collector) to a voltage source through pull-up resistor R_P to obtain anticipated output
- Can drive an analog device if capable of sinking adequate current. If not, need to use another more “powerful” transistor

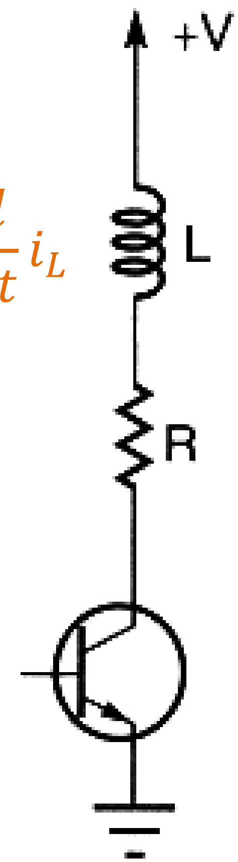


DRIVING INDUCTIVE LOADS REQUIRES EXTRA CARE

- Inductive loads are very common in electro-mechanical devices, e.g. motors, solenoids, and voice-coil motor etc.

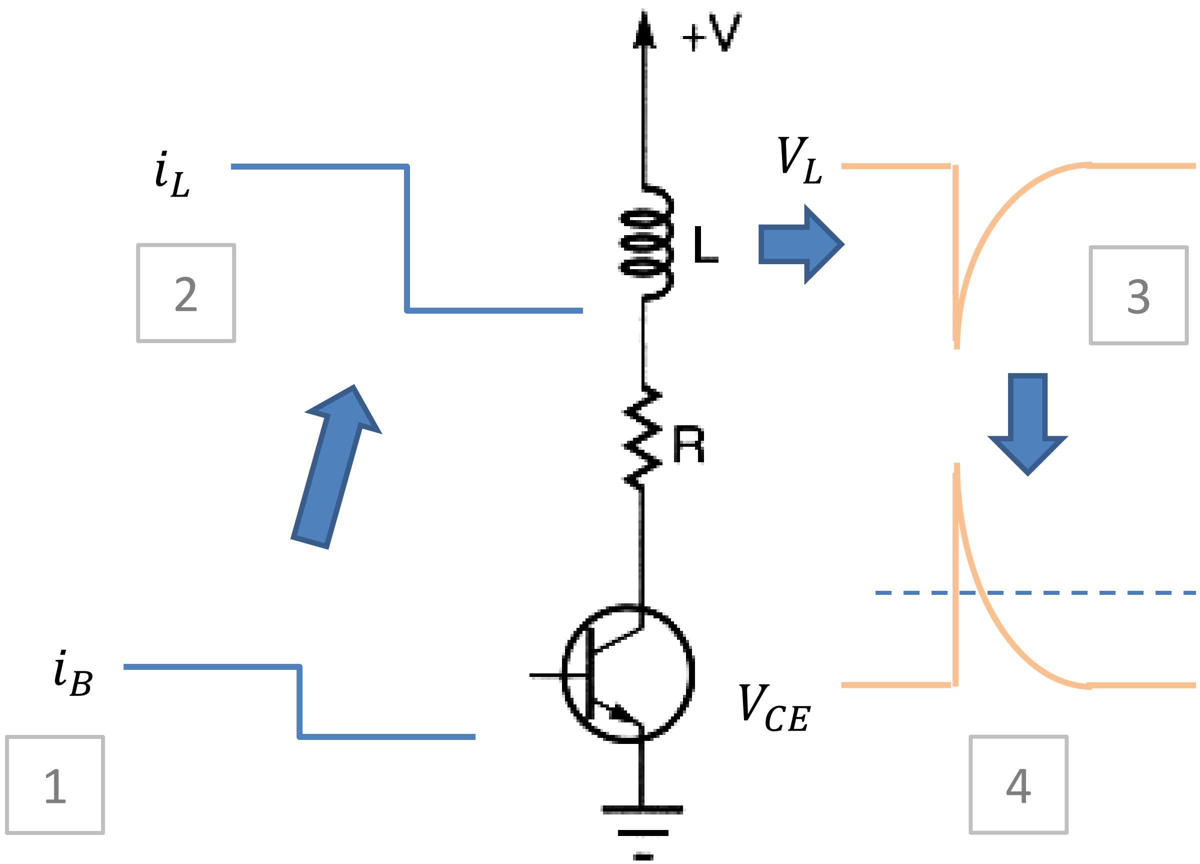
- A large voltage will build-up across the inductor when the inductor current is switched off. This voltage can be large enough to damage the transistor (inductor kickback)

$$V_L = L \cdot \frac{d}{dt} i_L$$



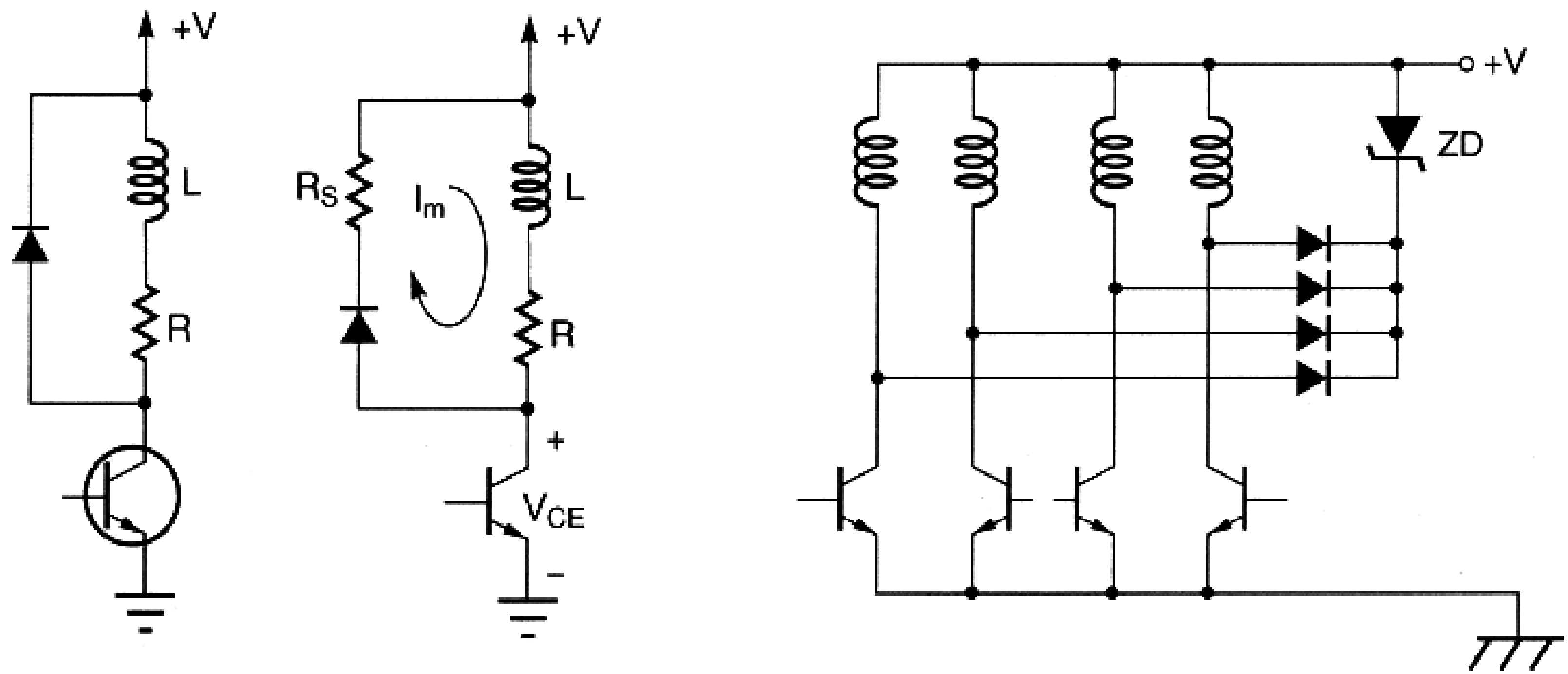
DRIVING INDUCTIVE LOADS REQUIRES EXTRA CARE

$$V_L = L \cdot \frac{d}{dt} i_L$$



Negative V_L means connection between inductor L and resistor R is at a higher voltage than source voltage +V

A FREEWHEELING DIODE CAN SHUNT THE INDUCTIVE LOAD



- Also called a flyback, kickback, or snubber diode
- Induced current circulates in a closed loop until dissipated
- Protects the transistor!

OPERATIONAL AMPLIFIERS PERFORM MANY USEFUL TASKS

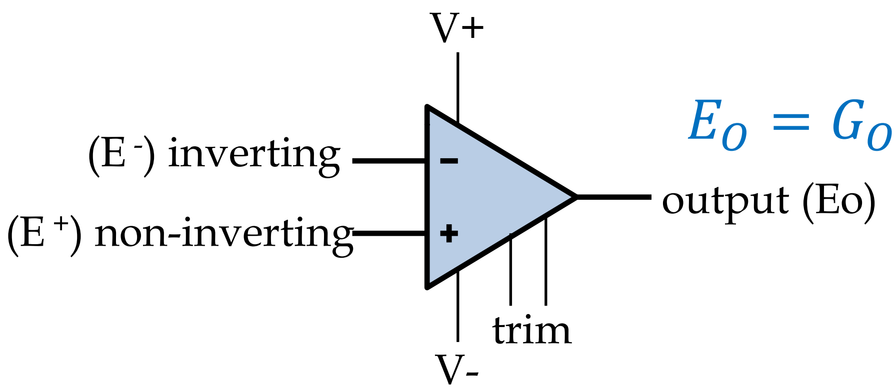
741 Op-amp – an industry standard

Image: http://www.tandyonline.co.uk/741-operational-amplifier.html

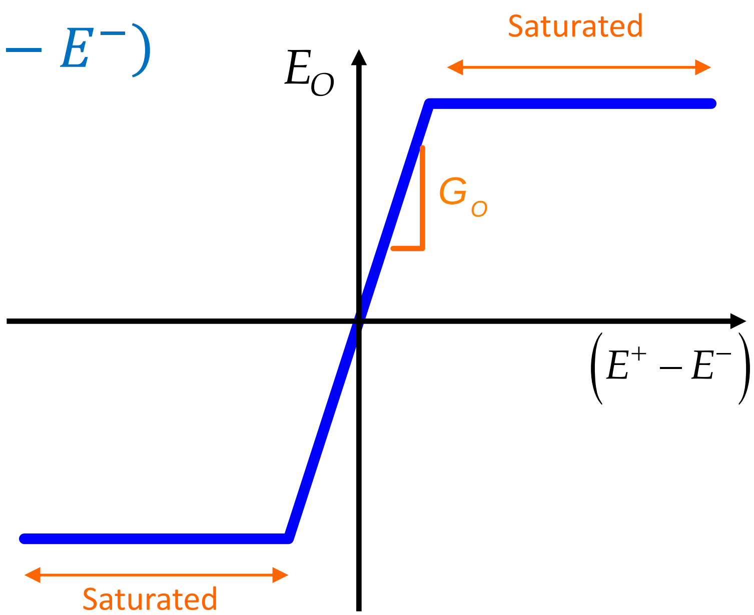
- Addition
- Subtraction
- Amplification
- Integration
- Filtering

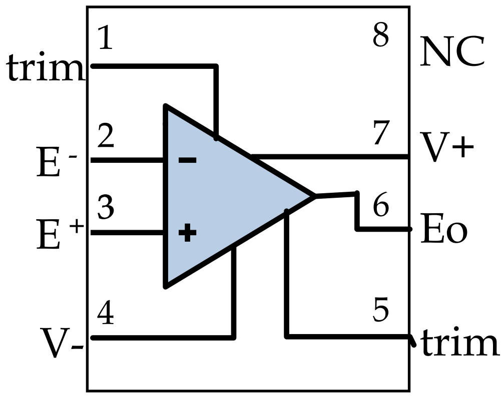
OP-AMPS AMPLIFY THE INPUT VOLTAGE DIFFERENCE

- Output driven in positive direction when E+ > E-
- Output driven in negative direction when E- > E+

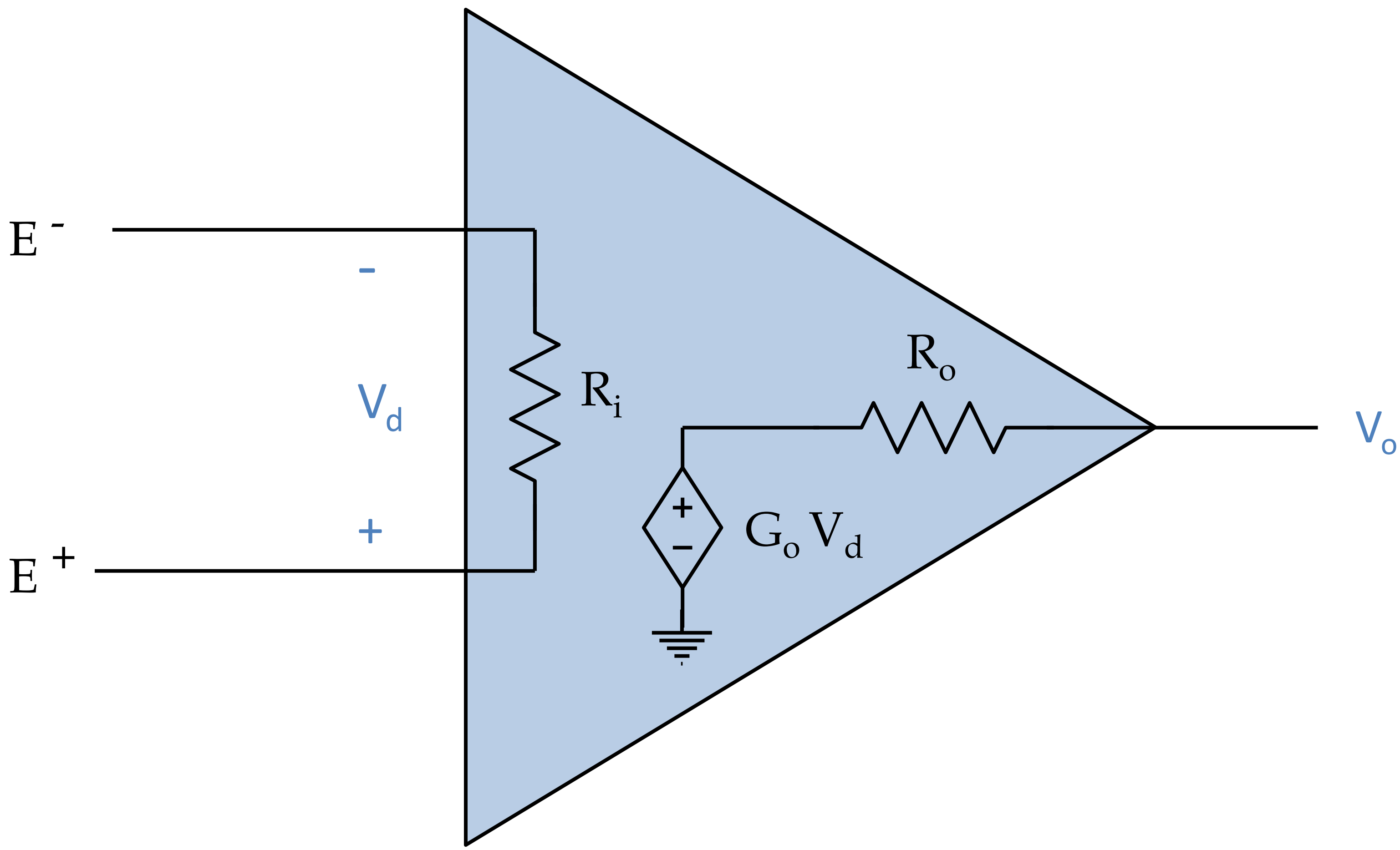


$$E_O = G_O(E^+ - E^-)$$



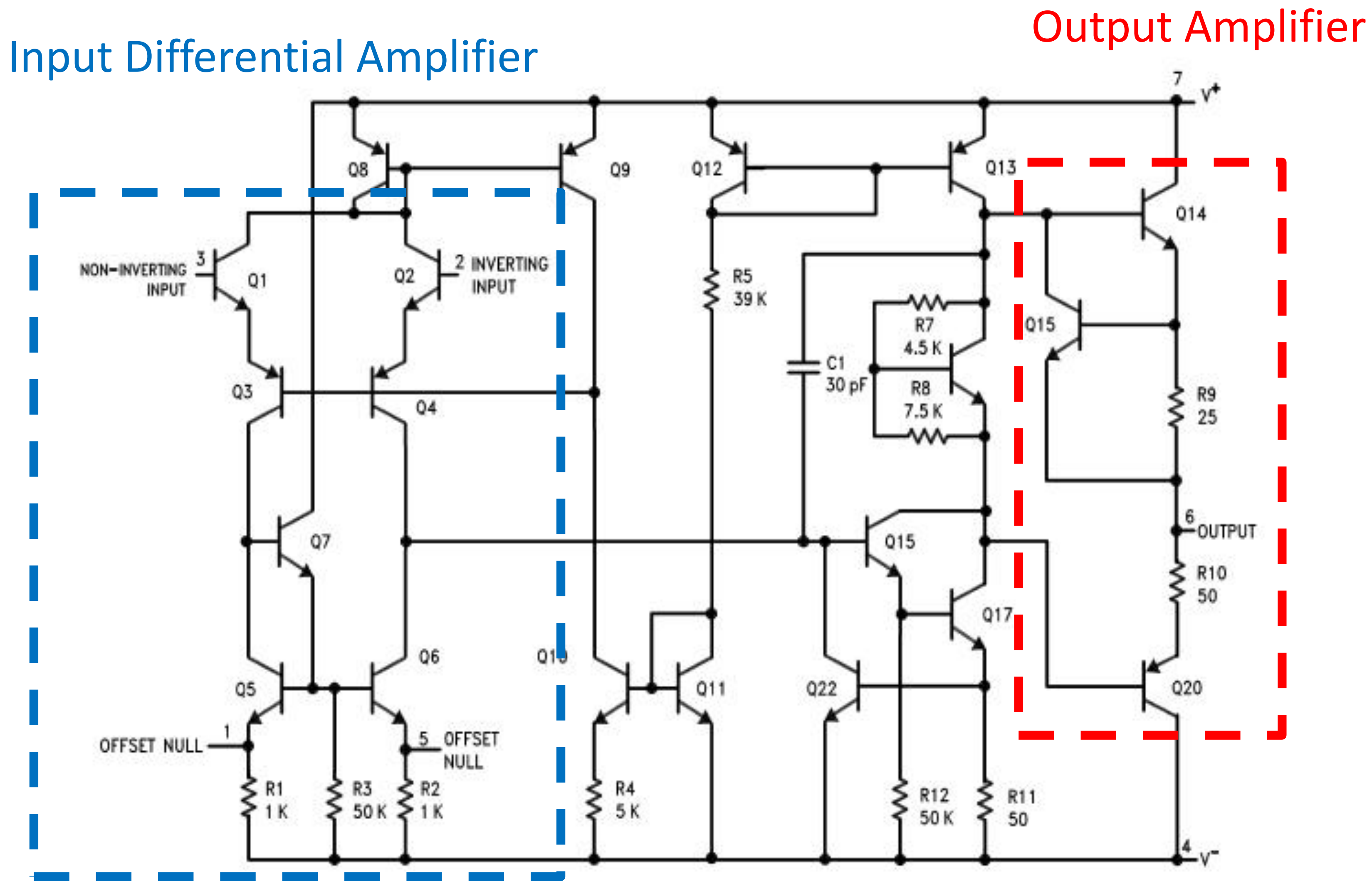


OP-AMP MAY BE MODELLED AS A LOAD AND CURRENT SOURCE



WHAT'S INSIDE?

741 op-amp schematic



OP-AMP CHARACTERISTICS

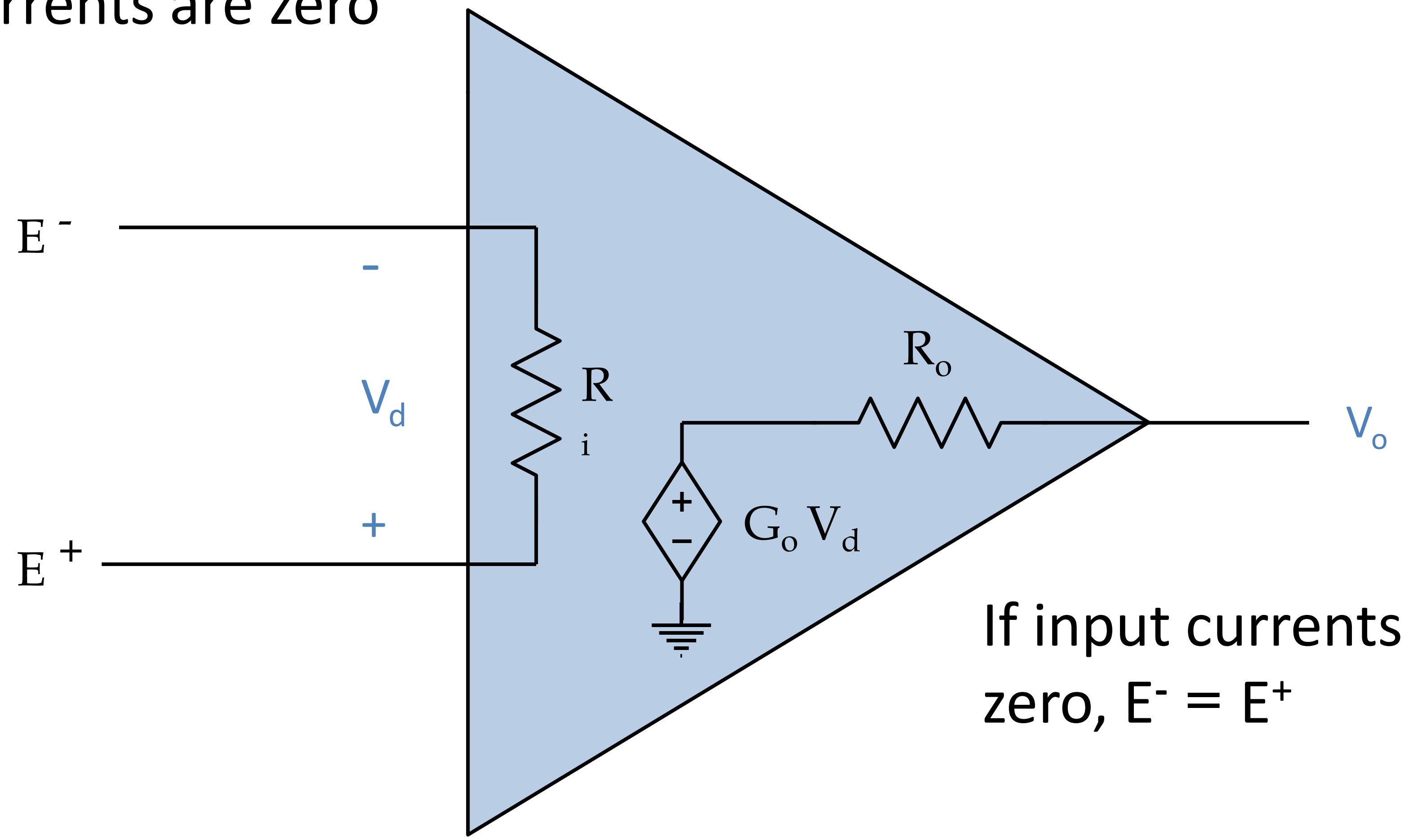
Ideal		Reality
Infinite	**High Open Loop Gain**	10^4 to 10^6
Infinite	**High Input Impedance**	300 KΩ to 1000 GΩ
0	**Low Output Impedance**	10 Ω to 5 KΩ (150 – 200 Ω typical)
Infinite	**High Bandwidth**	0.5 to 15 MHz
0	**Zero Offset**	0.1 to 5 mV

Implications:

- Seldom used in open-loop mode
- Almost exclusively used in feedback mode

OP-AMP MODEL

If $R_i = \infty$, input currents are zero



If input currents are zero, $E^- = E^+$

THE GOLDEN RULES:

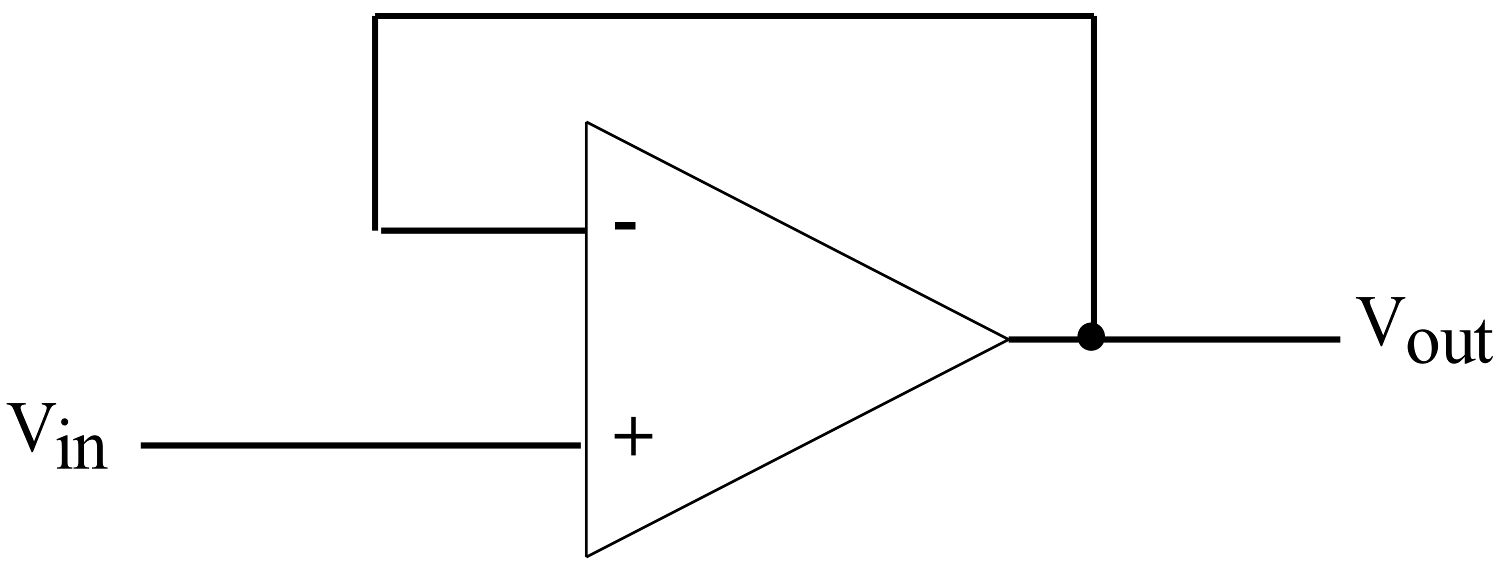
1. **The inputs draw no current**
   - Op-amp draws very little input current (0.5 mA for a 741C); we round it to zero for practical calculation.
2. **Inverting and non-inverting inputs remain at the same voltage**
   - The op-amp will do whatever is necessary to make the voltage difference between the inputs equal zero. It "looks" at the input terminals and changes its output voltage such that the external feedback network brings the input difference to zero.

These rules only apply when the op-amp is operated:

- Within its listed specifications
- In negative feedback mode

TYPICAL USAGE

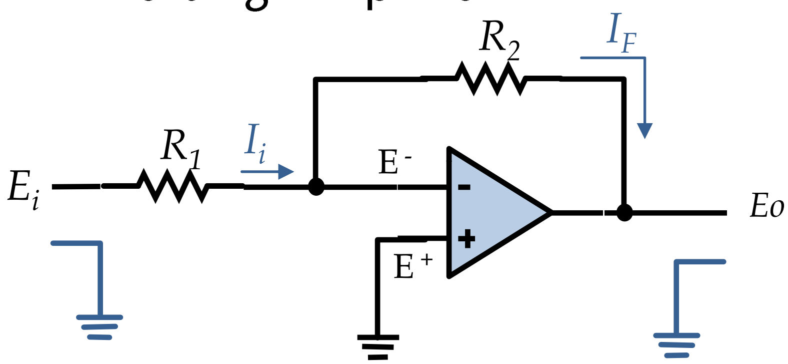
Negative feedback in this example, $V_{out} = V_{in}$



Q: What type of circuit is this? How can it be used?

OP-AMP EXAMPLES

- Inverting Amplifier

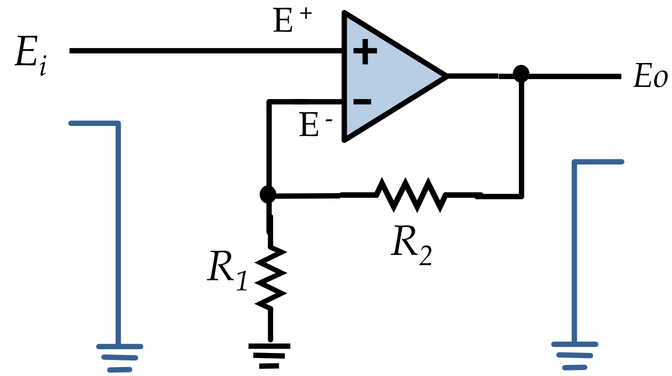


$$\frac{E_i - E^-}{R_1} = I_i = I_F = \frac{E^- - E_O}{R_2}$$

$$E^- = E^+ = 0$$

$$\frac{E_O}{E_i} = -\frac{R_2}{R_1} \quad \Rightarrow E_O = -\frac{R_2}{R_1} E_i$$

- Non-inverting Amplifier



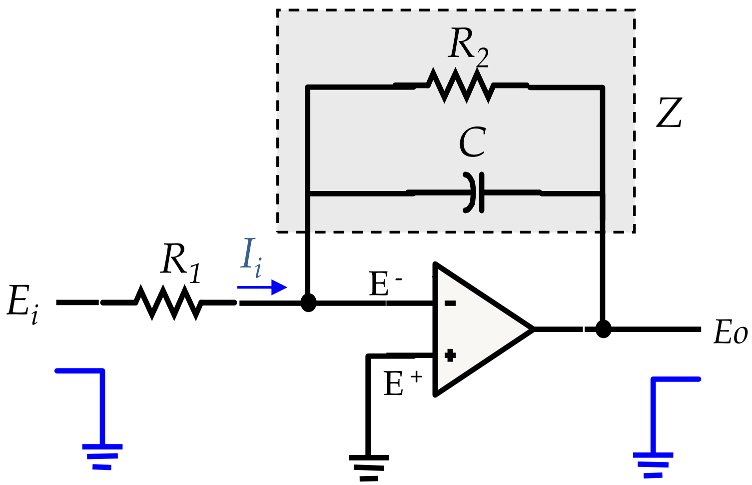
$$E_i = \left(\frac{R_1}{R_1 + R_2}\right) E_O \Rightarrow \quad E_O = \left(\frac{R_1 + R_2}{R_1}\right) E_i$$

$$E_O = \left(1 + \frac{R_2}{R_1}\right) E_i$$

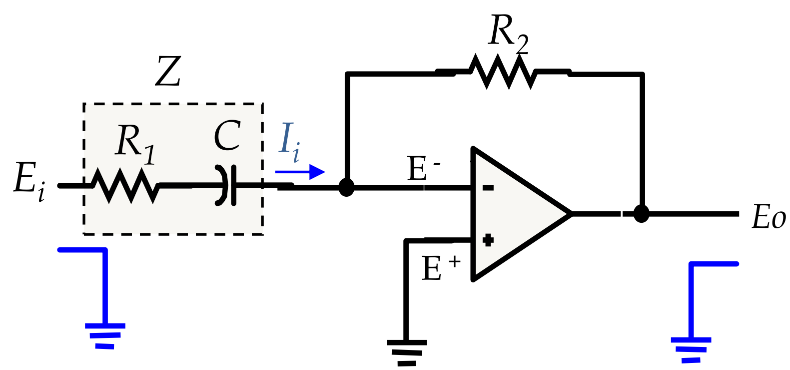
Q: What if $R_2 = 0$ *and* $R_1 \to \infty$*?*

OP-AMP EXAMPLES

- Low Pass Filter



- High Pass Filter



$$Z = \frac{1}{\frac{1}{R_2} + j\omega C} = \frac{R_2}{1 + j\omega R_2 C}$$

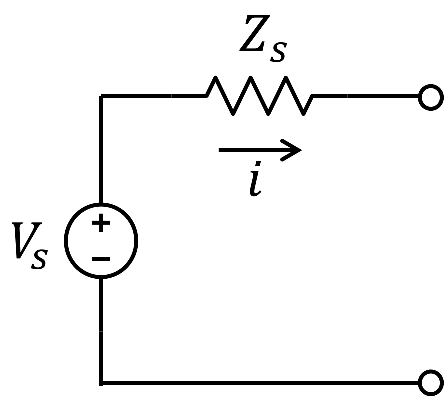
$$Z = R_1 + \frac{1}{j\omega C} = \frac{j\omega R_1 C + 1}{j\omega C}$$

$$\frac{E_O}{E_i} = -\frac{R_2}{R_1} \cdot \frac{1}{j\omega R_2 C + 1}$$

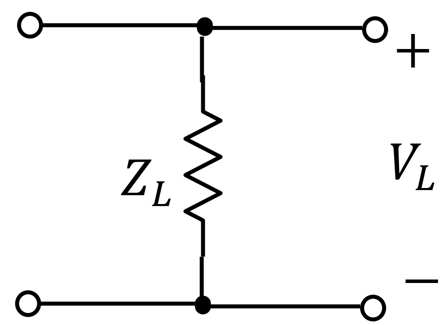
$$\frac{E_O}{E_i} = -\frac{R_2}{R_1} \cdot \frac{j\omega R_1 C}{j\omega R_1 C + 1}$$

IMPEDANCE INFLUENCES SIGNAL TRANSFER

Thevenin Equivalents:

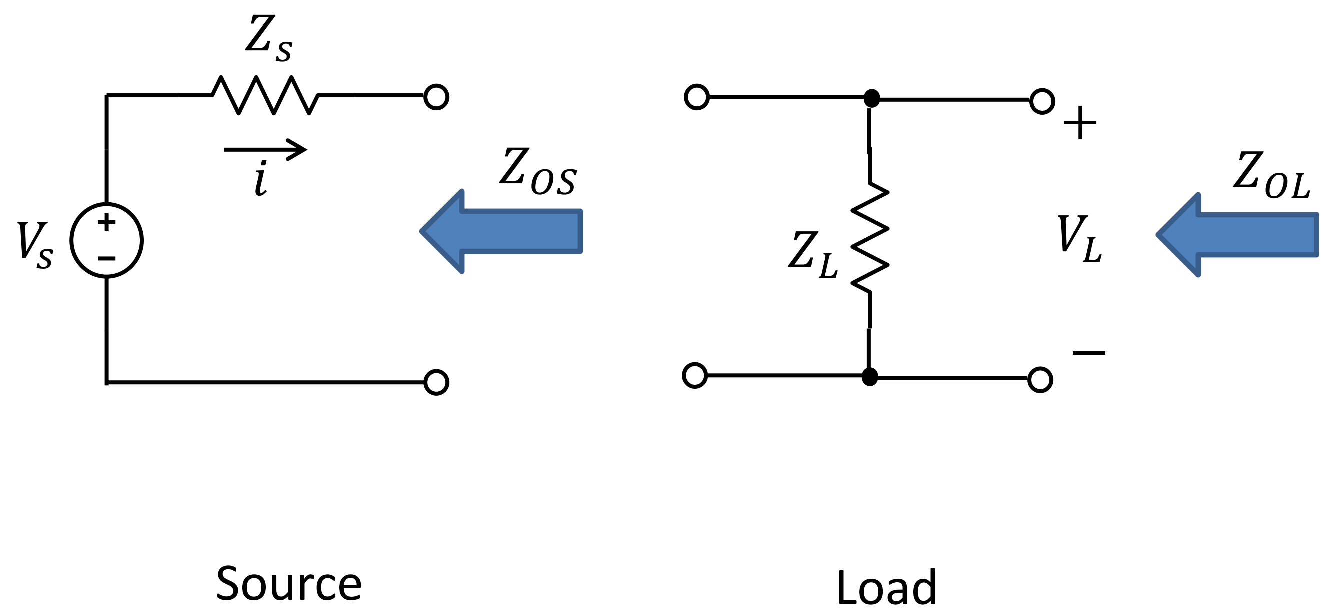


Source

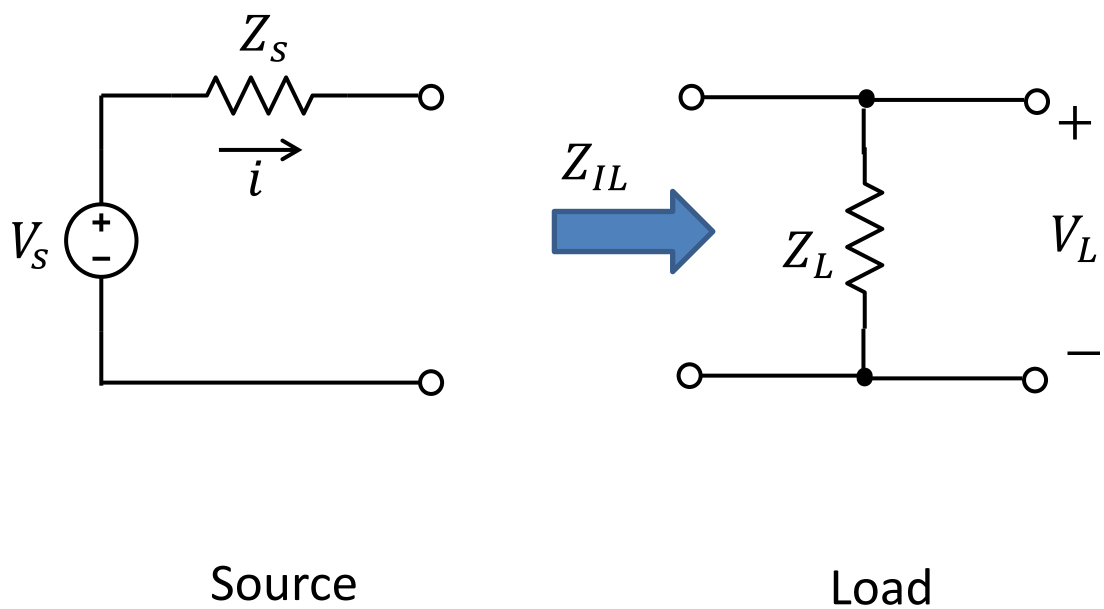


Load

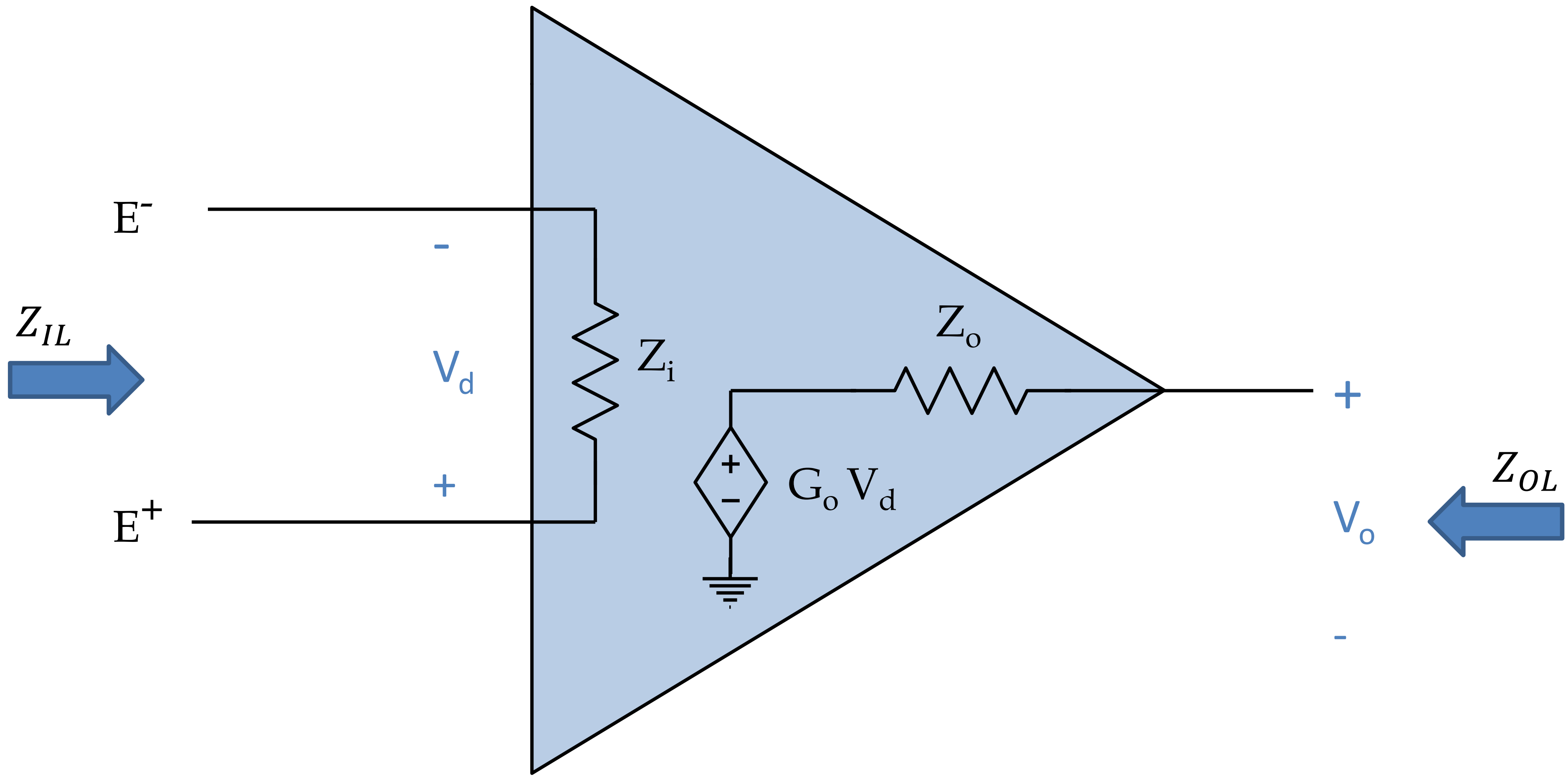
OUTPUT IMPEDANCE LOOKS "BACK" FROM OUTPUT



INPUT IMPEDANCE LOOKS "FORWARD" FROM INPUT

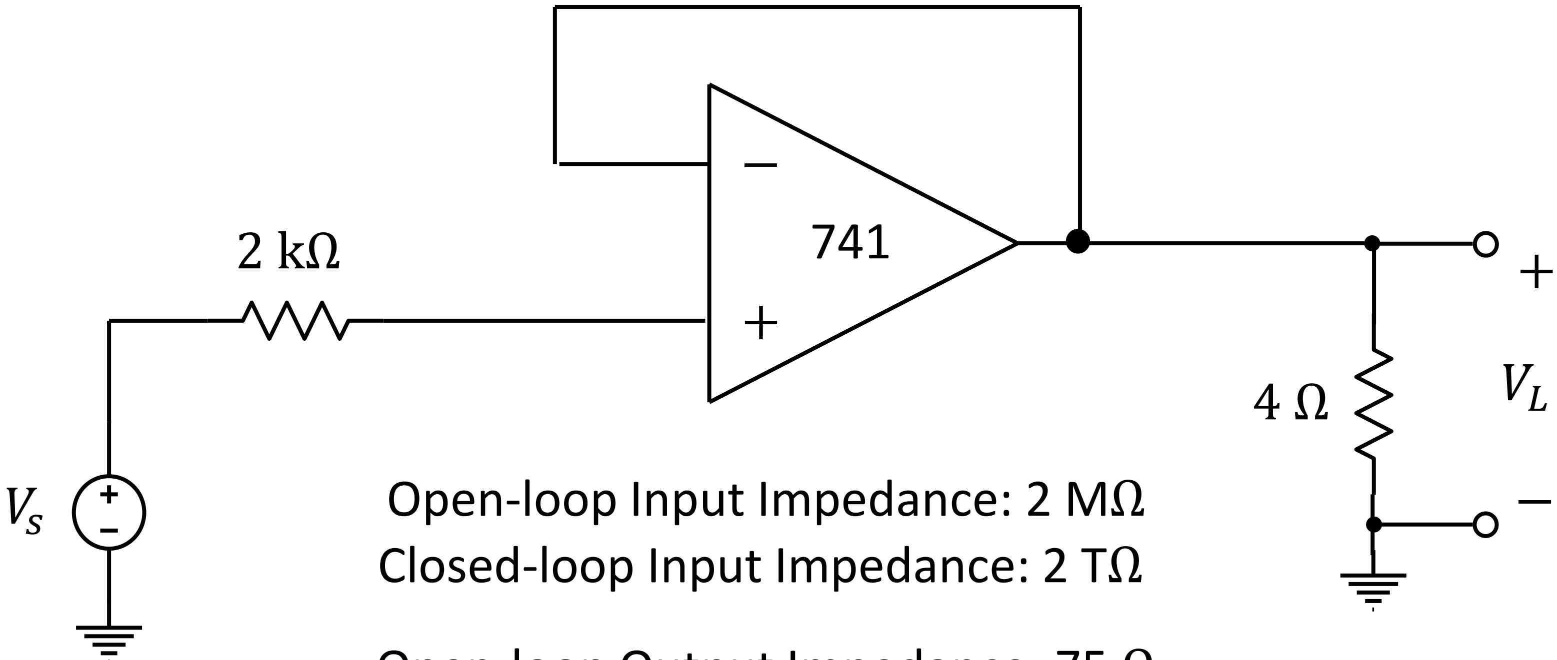


OP-AMP IMPEDANCE



Input and output impedances may be vastly different!

FEEDBACK ALTERS OP-AMP IMPEDANCE



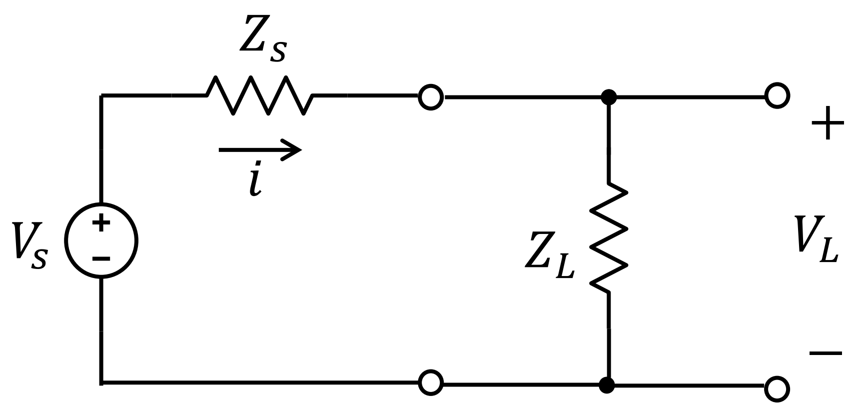
Open-loop Input Impedance: 2 MΩ
Closed-loop Input Impedance: 2 TΩ

Open-loop Output Impedance: 75 Ω
Closed-loop Output Impedance ≈ 0 Ω

Without op-amp: $V_L = \frac{4\ \Omega}{2004\ \Omega} V_s = .002\ V_s$

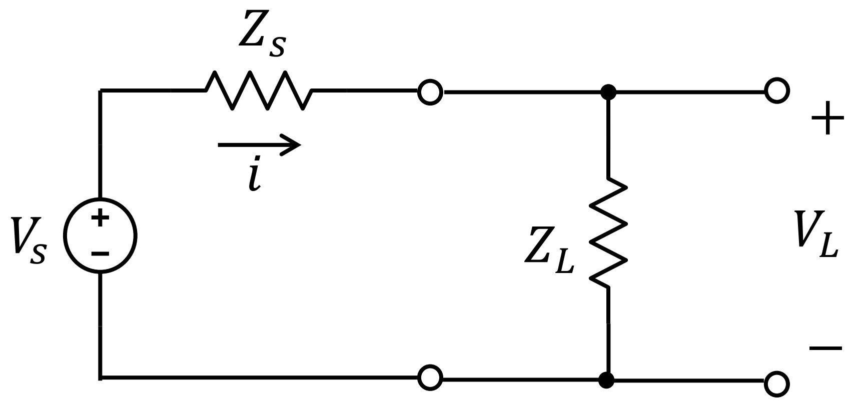
With op-amp: $V_L \approx V_s$ (as long as output is not saturated)

HIGH INPUT IMPEDANCE IS USUALLY DESIRED



Want $Z_L \gg Z_S$: $$V_L = \underbrace{\frac{Z_L}{Z_S + Z_L}}_{\to 1} V_S$$

IMPEDANCE MATCHING MAXIMIZES POWER TRANSFER

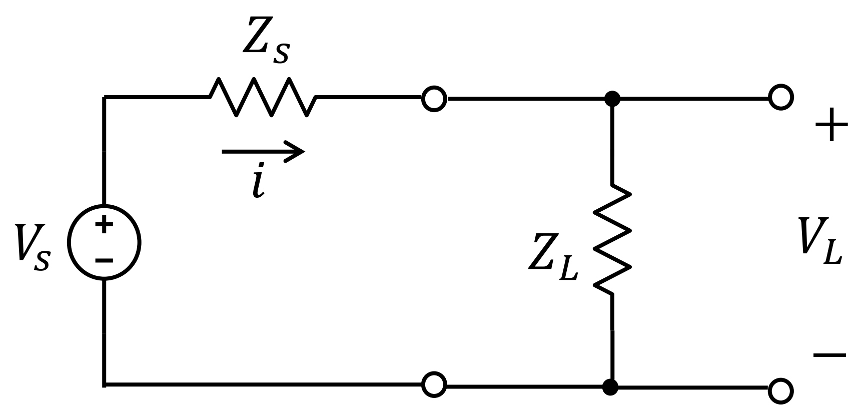


$$P_L = V_L\, i = \left(\frac{Z_L}{Z_S + Z_L} V_S\right)\left(\frac{V_S}{Z_S + Z_L}\right) = \frac{V_S^{\,2}}{\frac{Z_S^{\,2}}{Z_L} + 2\,Z_S + Z_L}$$

$$\frac{d}{dZ_L}\left(\frac{Z_S^{\,2}}{Z_L} + 2\,Z_S + Z_L\right) = 1 - \frac{Z_S^{\,2}}{Z_L^{\,2}} = 0 \Longrightarrow \frac{Z_S^{\,2}}{Z_L^{\,2}} = 1$$

$$\therefore Z_S = Z_L$$

MAXIMIZING POWER TRANSFER DOES NOT MAXIMIZE EFFICIENCY!



$P_S = V_S\, i$

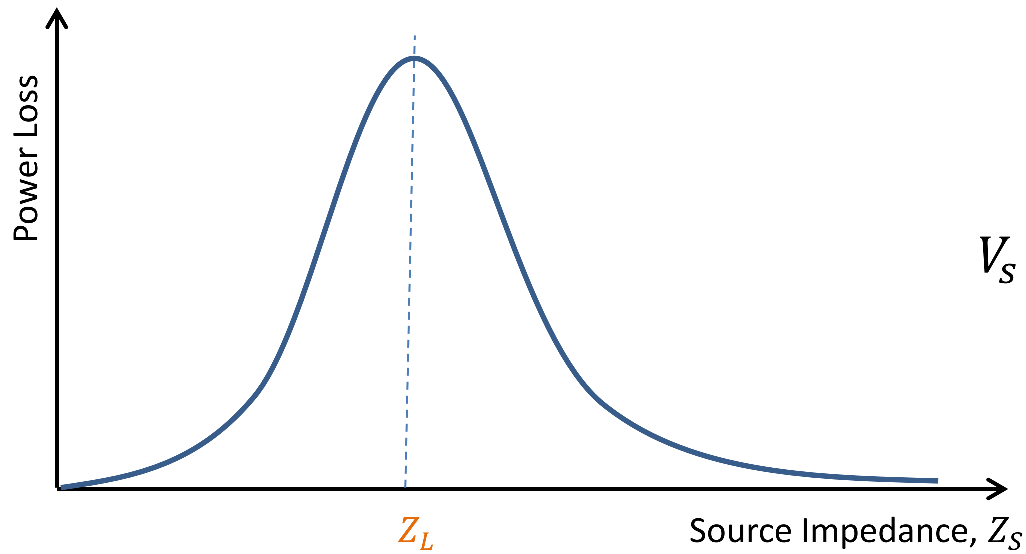
$P_L = V_L\, i = \frac{Z_L}{Z_S+Z_L} V_S\, i$

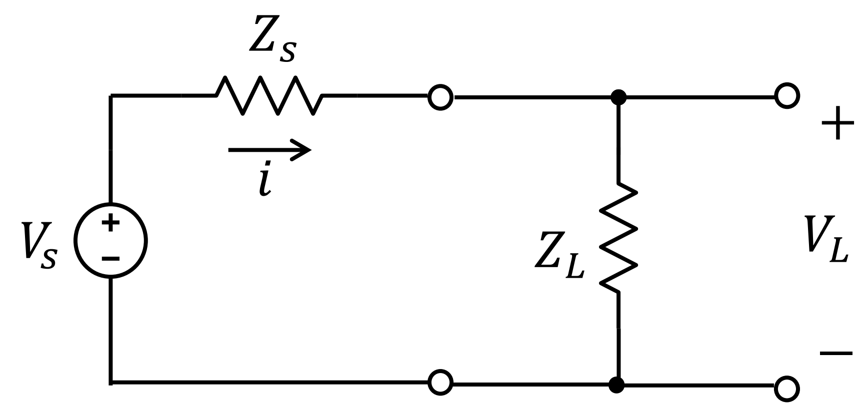
$$\eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S+Z_L}$$

At max power transfer, $Z_L = Z_S$ and $\eta = 0.5$

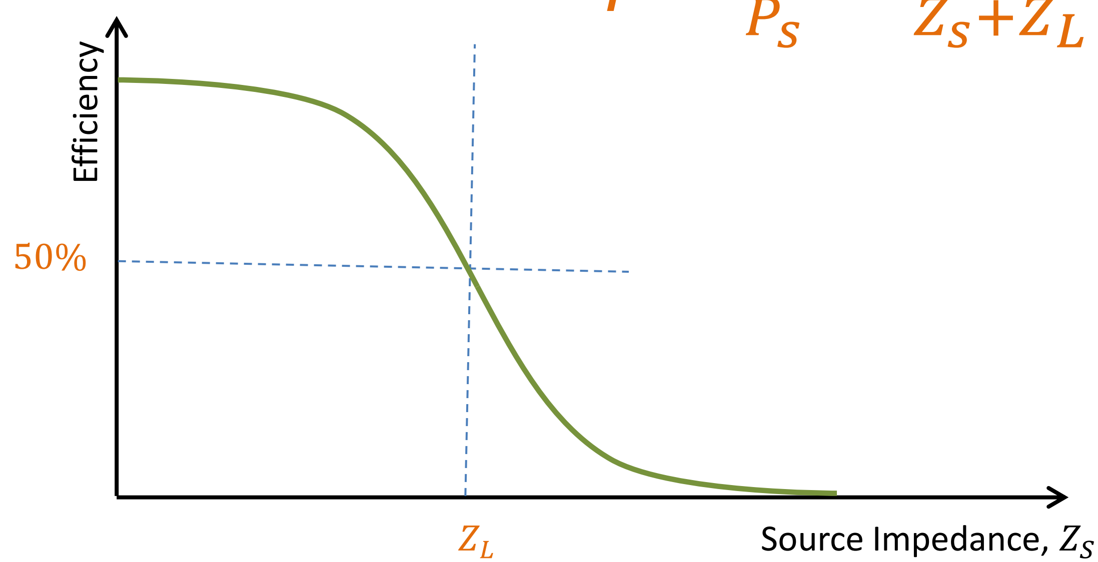
However, $\eta > 0.5$ when $Z_L > Z_S$

POWER LOSS VARIES WITH IMPEDANCE RATIO

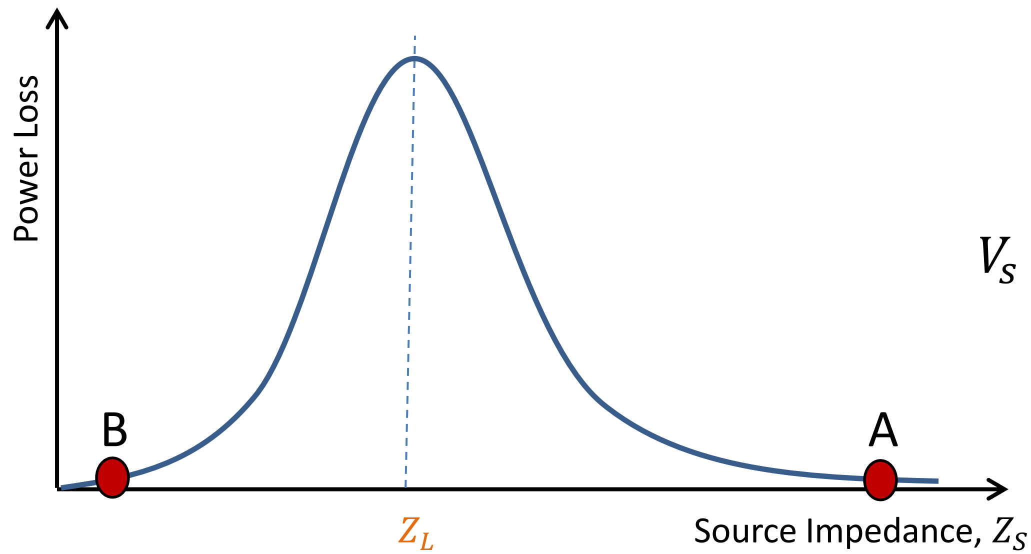


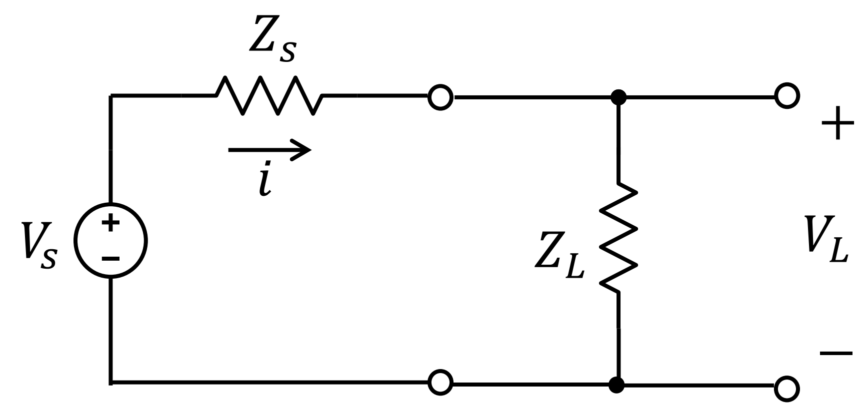


$$\eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S + Z_L}$$

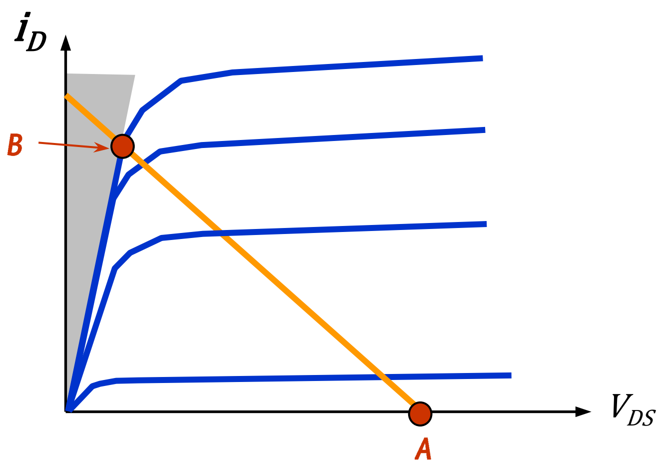


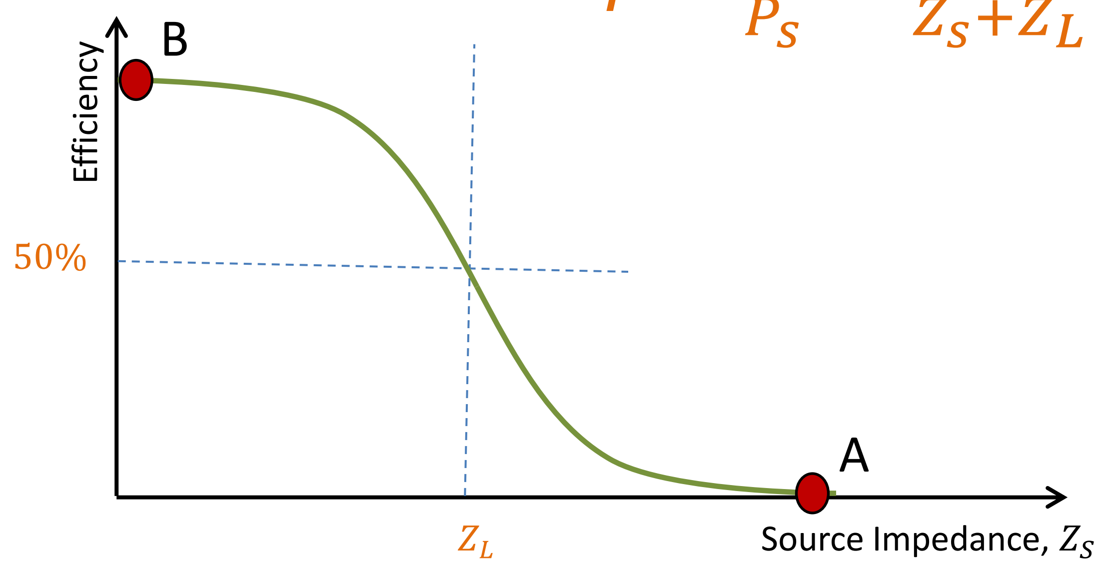
POWER LOSS IS MINIMIZED AT SWITCH POINTS





$$\eta = \frac{P_L}{P_S} = \frac{Z_L}{Z_S + Z_L}$$





COMING UP…

Computer Systems

- Why do computer systems matter?
- Combinational logic
- Sequential logic
- Finite state machines